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Modelling pit wall erosion using photogrammetry, implications for water quality, and acid and metalliferous drainage assessment

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Abstract

Exposed pit walls are prone to affecting water quality due to erosion caused by weathering. This work presents an updated case study from the high-sulphide Martabe gold mine in Indonesia, where a novel approach has been taken to assess spatial and temporal variations in pit wall erosion rates which influence debris generation and pit lake water quality. Understanding erosion rates of different alteration lithologies and waste classes enables forward planning and enhanced control over levels of acid and metalliferous drainage (AMD). Measurement of several test zones was undertaken using drone-mounted photogrammetric scanning targeting key lithotypes. The resulting 3D point clouds were used to generate digitised high-resolution surface meshes. Surfaces were remeasured at regular intervals and compared to the initial control surface to generate a 4D difference model. Observed differences show where material has been lost through dissolution and collapse or gained through the formation of scree piles. A key aspect of the study was the addition of manual debris and run-off collection in a series of small test pits to calibrate the findings of digital monitoring and provide important data relating to water quality and material characterisation. The net volumetric difference and calibrated mass of material removed was used to estimate the total amount of mass lost from each test area and extrapolated over the entire exposed pit surface before being forward modelled over periods of decades and centuries using a rate of erosion per unit area per unit time for each of the key lithotypes and waste classes encountered at the Martabe site. The mass and character of material removed plus run-off water quality were used to predict potential long-term AMD release incorporating 3D grade control block models developed during active mining.

Keywords: *erosion, pit wall, AMD, photogrammetry, water quality*

1 Introduction

Pit wall erosion within mining voids is a natural process related to weathering which results in material being removed from the pit wall as solid particulate matter or by dissolution. Whilst the erosion is consistent with naturally occurring processes in areas outside of the mine void, the rate of erosion from exposed pit walls of the type shown in Figure 1 is observed to be higher than would be expected in the surrounding established natural hillside setting where vegetation and soils reduce denudation rates. Pit wall erosion is a relatively passive process involving mostly low energy mass transfer, however, where pit walls consist of materials with elevated or reactive sulphide and/or metal/metalloid content, the process can affect water quality (run-off from the pit walls and the collection of standing water within the pot void), leading to acid and metalliferous drainage (AMD). Long-term erosion rates and AMD generation rates from pit walls can, based on industry experience and published literature, be challenging to model and are therefore often not well constrained, resulting in uncertainty with regards to closure planning, e.g. whether to favour pit lakes or pit fill methodologies. Proactively identifying potential sources of current and future erosion and estimating

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potential loading rates more accurately provides an opportunity to design mitigating steps to help reduce erosion, e.g. designing engineering solutions such as pit wall regrading, stabilisation, cover systems and revegetation. This also assists with the determination of requirements for water treatment, e.g. lime dosing in dedicated run-off collection ponds.

Several factors were taken into consideration when planning the pit wall erosion study, including the requirement to deliver on guideline principles relating to AMD and wider environmental management standards adopted by PT Agincourt Resources (PTAR) and the Martabe mine site. These principles include the necessity to comply with applicable environmental laws, regulations and operating permits, the prevention of pollution, the safe disposal of tailings and waste rock, successful implementation of mine closure, protection of biodiversity and continual improvement in environmental performance. This paper seeks to demonstrate the benefits of a proactive approach to closure planning and mine site rehabilitation which can potentially yield tangible long-term benefits for the operator, nature and local communities.

Figure 1 Ramba Joring pit wall showing advanced argillic alteration (brown) and argillic alteration (grey-white)

Collaborating with mine operator PTAR, Mine Environment Management (MEM) designed a targeted and highly practicable study to investigate the use of drone-mounted technology to estimate rates of erosion at the Martabe mine, Indonesia. The study sought to yield a better understanding of relationships between factors such as rainfall rates and aspects of geology including host rock lithology, composition, geochemistry and alteration mineral assemblages under the collective term “material competency”, all of which appear to be influencing erosion based on initial observations made during routine operation and environmental monitoring of the mine. Martabe is a high sulphidation epithermal gold deposit with multiple active open pits and an active AMD management policy seeking to demonstrate best in class environmental governance.

Prior to this study commencing, the host materials were divided on their alteration characteristics. This characterisation yielded five assemblages: argillic (AR), advanced argillic (AA), silicic (SI), propylitic (PR) and unaltered materials (UA). The most abundant assemblages in the geological model were AR and AA. The most abundant pit wall outcrops were therefore assumed to be argillic (AR) and advanced argillic (AA). Lesser amounts of SI, PR and UA materials were expected. Average low-, mid- and high-case erosion rates for AR material across the various pit voids at the Martabe site were roughly estimated at approximately 0.02, 0.05 and 0.1 m/yr, respectively. Lower rates of 0.005, 0.01 and 0.02 m/yr were estimated for AA material which was expected to be on average more competent based on blasting data.

Whilst a key aspect of the overall study remained the comparison between different material types exposed in the pit walls, focusing on AR and AA alteration, the primary aim of site-specific trials undertaken at the Barani and Ramba Joring pit voids was to understand in more detail how differences in composition and competency of the pit wall rock affects erosion rates of the pit walls over time. The results would, if informative, be used to guide closure planning, e.g. to determine if pit lakes or opting for pit filling as a means of re-using void space would be the optimal solution. In addition to alteration type, variables such as sulphide content and buffering capacity collectively quantified using net acid generation (NAG) acidity as an industry standard measure, rainfall rates, erosion rates and run-off water quality are all measured as part of this study in an effort to monitor and detect real-world changes that can be factored into source term modelling scenarios. An example of a waste material classification scheme used at the Martabe site which is based on NAG and buffering capacity in the form of carbonate is provided in Table 1. Quantifying the amount of each class of material and how that relates to measurable erosion rates of that material presents a significant challenge; one which this study helps to address.

The NAG acidity (kg H_2SO_4 equivalent) classification scheme illustrated in Table 1 considers the net result of all acid-forming and acid-neutralising reactions. For this reason, Class 1 material, which is considered environmentally inert and useful as a cover material, is distinct from Class 3, which is expected to be reactive and has the capacity to leach metals as part of drainage processes if no mitigation steps are put in place.

Table 1 Example material classification scheme used at the Martabe mine

Class of material	Net acid generation acidity kg H_2SO_4	Comments and potential uses on site
Class 1	0	Clean unaltered, unmineralised soil or rocks, potential growth medium
Class 2	<5	Low-sulphide material used for infrastructure construction and growth medium
Class 3a	5–10	Potentially acid-forming (lower risk than Class 3) material used in certain circumstances for construction
Class 3	10–65	Potentially acid-forming material that requires management
Class 4	>65	Potentially highly acid-forming material that requires management
Class 5	Ca > 0.4%	Material with delayed onset acid generation presence because of elevated carbonate content

Research by the likes of Grohs & Pearce (2019) and the imagery exemplified in Figure 2 from waste classification and alteration modelling at the Ramba Joring pit were used to derive more detailed quantitative analysis, the results of which are presented in Figures 3 and 4. This initial preparatory work undertaken as part of the main field-based study indicated that across Barani and Ramba Joring, the argillic alteration (AR) suite makes up approximately 51% of the exposed pit wall and contains kaolinite, illite, smectite, dickite and montmorillonite, various aluminosilicates, and alunite. The AA suite makes up approximately 39% of the exposed pit wall based on visual analysis and shows greater proportions of alunite with lower proportions of illite and montmorillonite. Within the averages, Ramba Joring has a higher proportion of AR material exposed (with 55% against Barani with 35%), with Barani showing greater exposed AA (being 45% against 37.5% at Ramba Joring). Silicic materials make up the remaining c. 10% of the combined average but are considered stable from an erosion perspective, being extremely competent silica and minor alunite. At Martabe, non-ore mined materials are routinely separated to ensure efficient usage and storage onsite as part of an established waste management and valorisation system.

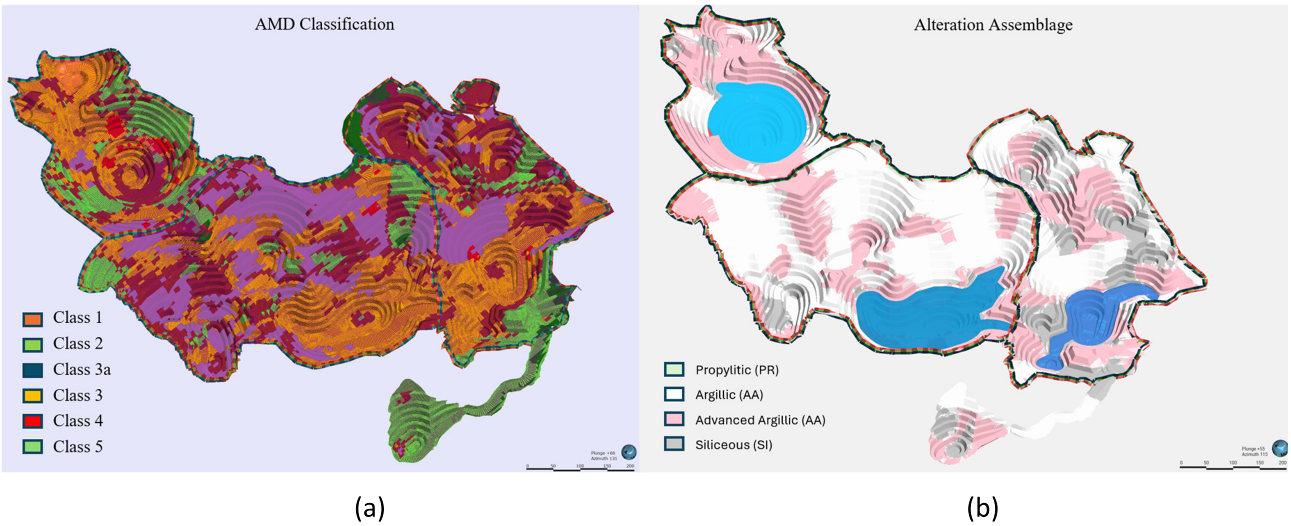


Figure 2 Examples of: (a) Acid and metalliferous drainage (AMD) material classification; (b) Alteration assemblages at the Ramba Joring pit (final depths of pit void development, estimated pit lake formation extents based on natural spill points are shown for illustrative purposes)

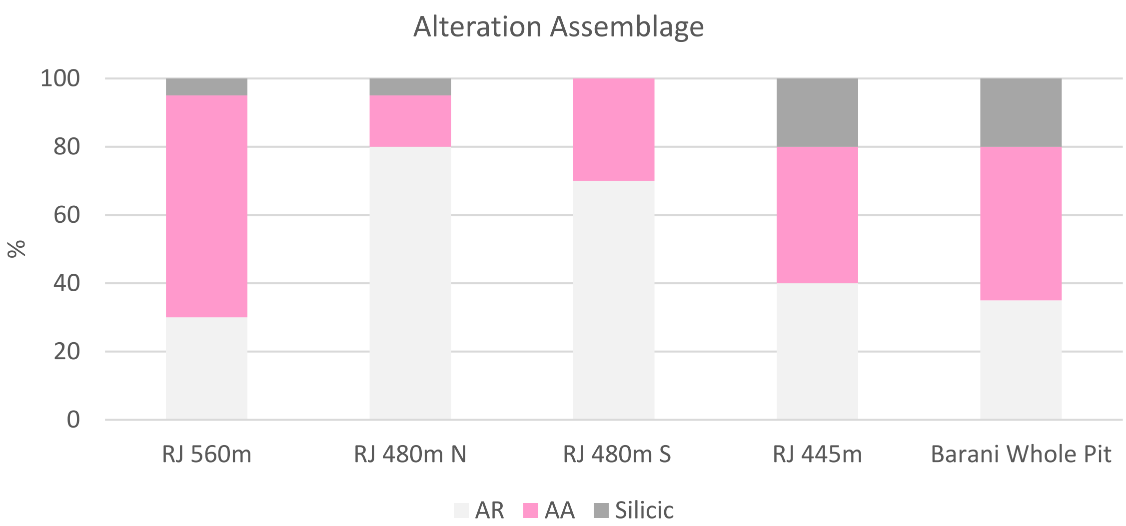


Figure 3 Alteration assemblage material classification for pit wall water catchments

The data presented in Figure 4 shows that Barani has a significantly different combination of waste classes when compared like for like with Ramba Joring at the pit scale. Barani is overall dominated by Class 3a material with minor components of Class 2 and Class 3. In contrast, three of the four main catchments at Ramba Joring show a dominance of Class 3 and Class 3a material with minor Class 2 and Class 5, but the most elevated catchment, referred to as the 560 m catchment, shows a dominance of Class 2 with lesser but equal proportions of Class 1 and Class 3a material. Capturing this natural variability and translating it into meaningful inputs for source term and water quality modelling are considered vital, in the context of this paper, for the delivery of meaningful guidance for long-term closure planning.

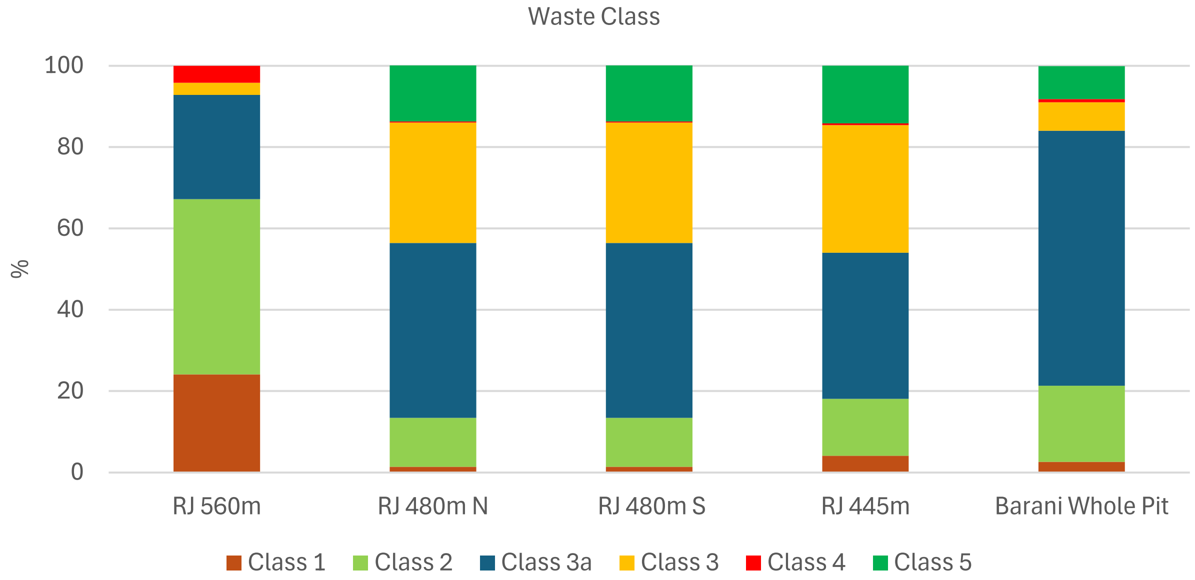


Figure 4 Acid and metalliferous drainage material classification for pit wall water catchments

2 Methods

The mine environment is an active setting with large-scale industrial processes occurring daily. Therefore, accurate and precise measurement requires reliable baseline data. Photogrammetry was selected as the most practicable means of collecting repeat spatially accurate and precise datasets in such an environment. In addition, manual measurement of material loss was attempted using active collection of solids and suspended fine particles in containers buried in small trial pits below local drainage catchments on the pit walls.

2.1 Spatial monitoring using photogrammetry

Photogrammetry is a technique that uses multiple overlapping photographs to create 3D models of objects, structures and landscapes. Early publications such as that of Chandler & Moore (1989) quickly recognised the potential value of analytical photogrammetry and its applications to the study of slope instability. The development of powerful computing algorithms now offers reduced noise and rapid processing of data to yield the derivation of displacement vectors for monitoring unstable slopes. In the case of Martabe, unmanned aerial vehicle drone surveys provide the raw input data which are compiled to produce landscape models and orthographic images. Photogrammetric surveys are ideally suited to the recording of subjects where consistent precision is required, e.g. monitoring short-term erosion of the Martabe pit walls. Another key aspect of photogrammetry is the ability to capture multiple datasets through time to see progressive weathering patterns. By assessing changes over time, it is possible to estimate the rate of erosion and loss of material by physical removal and dissolution, or deposition in the case of scree build-ups.

2.2 Manual collection of scree and run-off

The seven manual trial pit locations listed in Table 2 were identified by MEM as suitable for testing of the proposed erosion monitoring methods. These locations include four in the Barani pit and three in the Ramba Joring pit. The locations consider the six classes of AMD material from Table 1, the maturity of the existing weathering profile (fresh or weathered) and two main types of alteration assemblage identified as being important for controlling levels of AMD at Martabe (AA and argillic).

Table 2 List of sample locations where trial pits were positioned to collect run-off and debris

Test	Waste class	Alteration type (dominant)	Weathered/freshly exposed
B01 + BO2	2	Advanced argillic	Freshly exposed
B03	5	Argillic alteration	Freshly exposed
B04	3	Advanced argillic	Freshly exposed
R01	5	Argillic alteration	Weathered
R02	2	Argillic alteration	Weathered
R03	5	Advanced argillic	Freshly exposed

The seven trial locations are illustrated in Figure 5

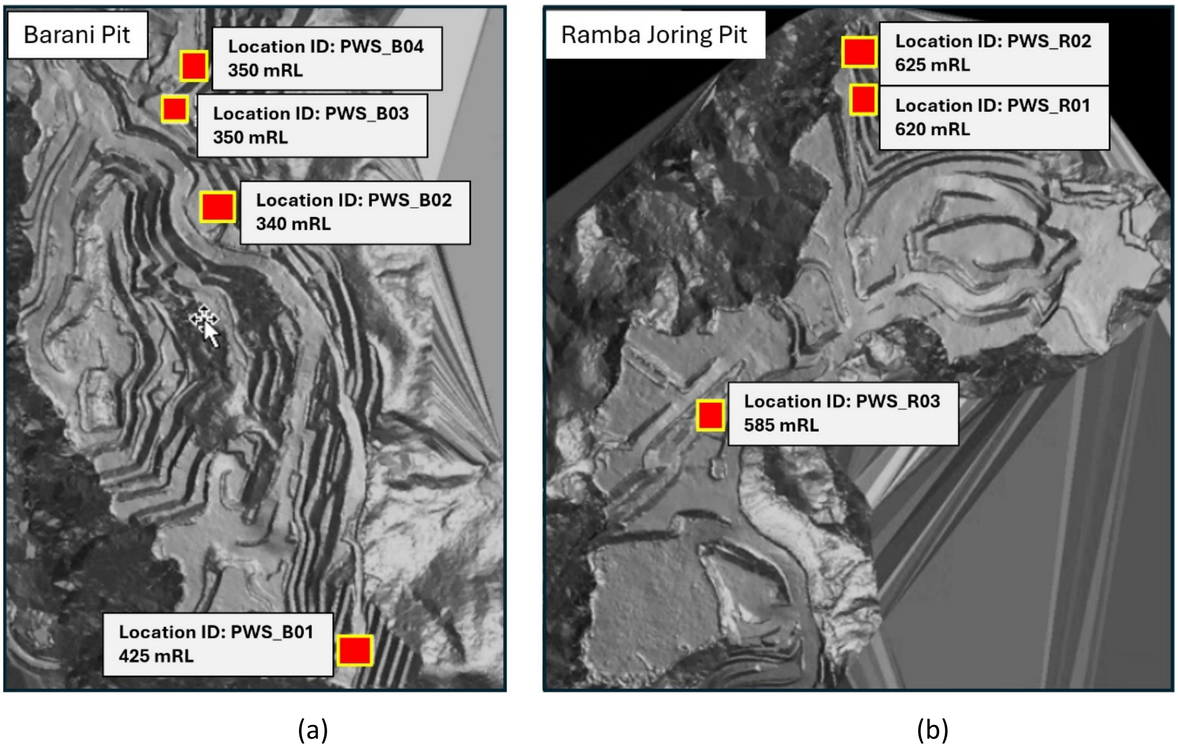


Figure 5 Images showing high resolution digital elevation model and trial locations for: (a) Barani pit; (b) Ramba Joring pit

Field trials of the type illustrated in Figure 6 sought to measure material movement directly and consisted of 3.0 × 1.0 × 0.5 m-sized trial pits excavated from the wall of the bench at each of the seven monitoring locations. The pits were lined with geotextile fabric and sumps were lined with HDPE to enable material collection and water sampling. Monitoring of the locations was undertaken by PTAR geologists every two weeks. The material removed from the trial pit was subsampled and sent for laboratory testing. The remaining material was placed into an intermediate bulk container (IBC). The IBC is used for large-scale kinetic testing to investigate long-term leachate production from transported materials. The trial pits sought to validate previous assumptions regarding eroded material reactivity and to inform mass loading rate estimations by material class and alteration type prior to potential pit infill testing. The field trial was designed to run for a minimum of 10 weeks. Material collected was tested for relevant geochemical parameters. Run-off water quality testing was also undertaken for each trial pit, with a focus on pH, electrical conductivity (EC), acidity and alkalinity, with sulphate as a proxy for sulphide oxidation and elemental assays for Ca, Mg, Na, K, Fe, Mn, Al, As, Cu, Ni and Zn as key indicators of metal release. Rainfall monitoring using conventional rain gauge systems was undertaken throughout the test period at each pit.

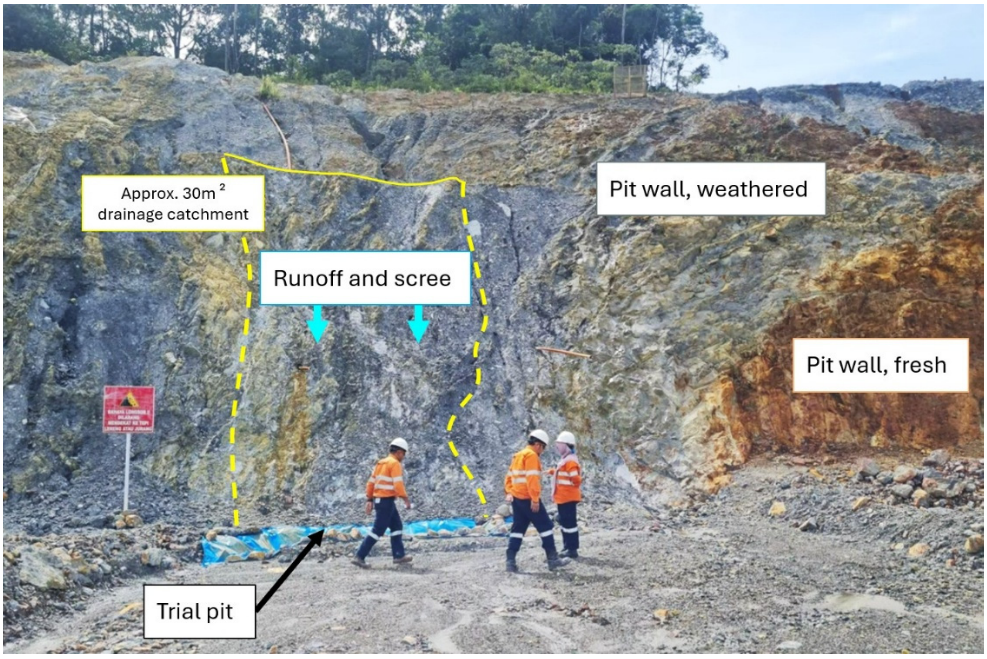
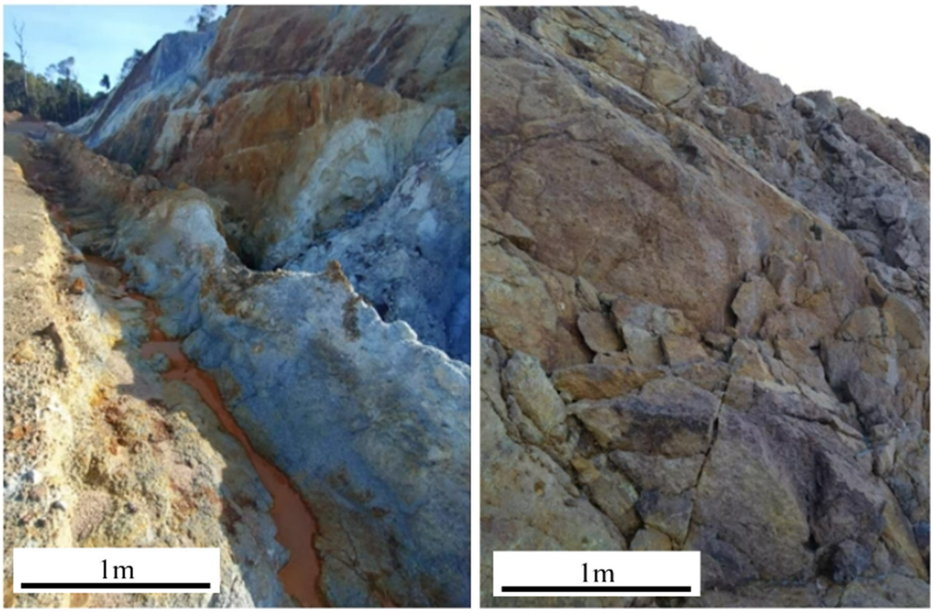


Figure 6 An example of a manual sampling trial in the Barani pit

3 Results

Empirical evidence during mine operation at Martabe had indicated the clay-rich AR assemblage is less competent and might be expected to erode at rates of up to five times the rate of the AA assemblage. However, there was also a strong counter argument that the presence of reactive sulphide in the AA material might function as a destabilising agent. The difference between the two assemblages has therefore been assessed at the Ramba Joring and Barani pit locations, which are considered representative examples of volcanogenic epithermal gold systems (e.g. Wright et al. 2021).

A visual inspection of the pit wall at Ramba Joring showed that “powdery” disaggregation followed by rapid washing during heavy rainfall was the dominant erosive mechanism for AR (Figure 7a). In contrast, the advanced AR showed “blocky” weathering to be the most likely form of mass material transfer (Figure 7b). Events which were observed to trigger erosional loss during the test duration included large rainfall and storm events, but it is noted that over the long term the occurrence of low-intensity tectonic movements and shaking related to earthquakes may also have an influence (these are a common occurrence in the Sumatran arc where Martabe is located). From an AMD perspective, the powdery dissolution of the argillic material is potentially important because the process liberates a large amount of fine suspended particles and has the potential for soluble species which, in the case of Classes 3, 4 and 5 material, could include metals. In contrast, the blocky AA material retained low surface volume, indicating a limited exposure of sulphide to the area. Thus, lower reaction rates than from argillic material would be expected for a given released rock mass.



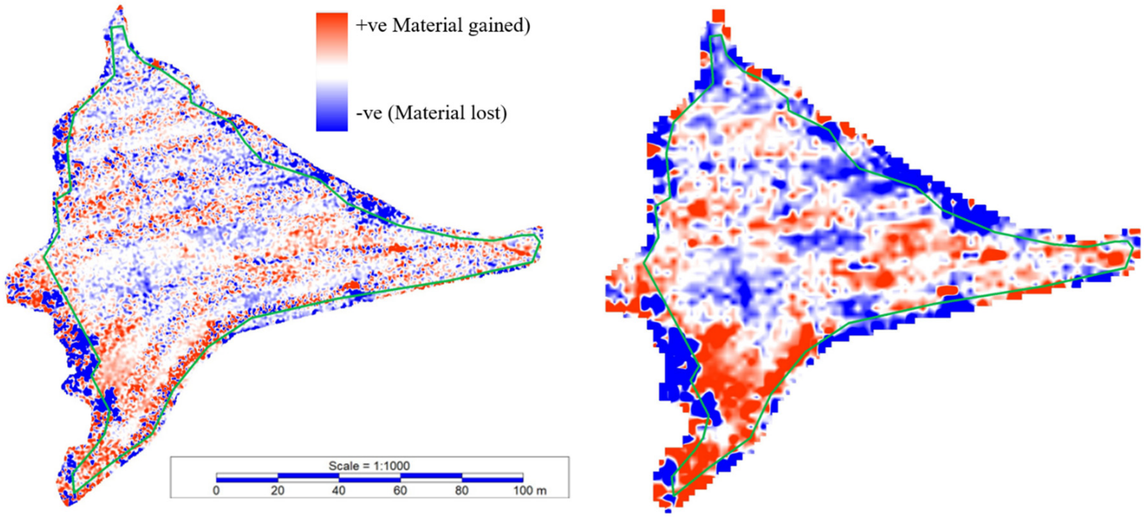
(a) (b)

Figure 7 Examples of: (a) "Powdery" disaggregation in a zone of argillic alteration; (b) Blocky weathering in a zone of advanced argillic alteration

3.1 Spatial monitoring using photogrammetry

Measurement of the pit walls surrounding the seven main trial pit locations was undertaken using drone-mounted photogrammetric scanning. The resulting 3D point clouds were derived from photogrammetry at the Barani and Ramba Joring pits. Data coverage is focused on the parts of the pit wall which drain directly into the trial pits. For each pit studied, scans were taken at approximately five-week intervals. The point cloud data were used to generate high-resolution digital surface meshes using both Seequent LeapFrog™ and IHS Markit Kingdom™ software platforms. Each point cloud dataset was gridded using a range of resolutions to investigate the effect of scale dependence in the measuring process and to determine at what point noise began to dominate real-world signals. The surface of the pit wall is inherently rough, with asperities at a great range of scales from millimetre to tens of metres. This presents a challenge when seeking to reconstruct the surface as a digital surface, e.g. how many data points are required and at what scale does roughness become insignificant. The ideal grid sampling resolution is at twice the Nyquist frequency to avoid aliasing (Nyquist 1928). The sampling frequency used in this study was determined based on the approximate wavelength of discernible features which, in the case of pit wall benches, are in the order of metres, whilst subtleties within the benches, such as tyre tracks, become visible in the order of decimetres. The surface reconstructions were therefore sampled at an appropriate resolution, based on operator discretion, to despike the data and reduce random noise whilst retaining sufficient sampling density to image features such as scree piles and boulders without unwanted aliasing.

A practicable solution based on trial and error was found by using a gridding resolution of 0.5 m, which provides a close match to the visible topography whilst mostly eliminating anomalies caused by grassy vegetation. Surfaces from different dates were compared to the initial control surface to generate 4D difference models. Observed differences show where material has been lost through dissolution and weathering or gained through the formation of scree piles. The net volumetric difference was used to estimate the total amount of mass lost from each test area at 0.5 m resolution with additional estimates made at resolutions of 0.25 to 2.5 m to provide a sensitivity check for resultant outputs (Figure 8). Considering the findings from geochemical testing of trial pit debris described in the following section, the estimated mass of material removed, calculated using the digital difference method, was then used to predict potential AMD release rates. The repeatability of the measuring method on inherently rough surfaces is accepted as a potentially limiting factor, especially during short-term tests where variations are small compared to the scale of measurement. The method described and used for this testing is expected to yield steadily improving accuracy over the longer-term life of mine, closure and post-closure development and monitoring phases as the amount of change becomes greater than the measuring uncertainties.



(a) (b)

Figure 8 Example of the photogrammetry subtraction method undertaken at two different gridding resolutions – (a) at 0.25 m and (b) at 2.5 m – on a pit wall area in the Barani trial to investigate the scale dependence and accuracy of the measuring techniques being used. The green line denotes the edge of dependable data

Calculations based on a volumetric variance between the first and last reference scans indicate up to 523 m^3 of material has been relocated on the Barani pit wall in an area dominated by AR over a period of 20 weeks. A volume of 523 m^3 is equivalent to approximately 1,255 t of material using an average density conversion of 2.4 t/m^3. Put another way, the total volume divided by the total area of the scan is equivalent to a 0.04 m thickness of material over the measured area of 13,454 m^2. Comparable results were obtained for Ramba Joring, suggesting annualised weathering rates for argillic material of up to 0.1 m/yr (based on 0.04 m over 20 weeks). Outcomes were at the top end of values predicted in existing estimates (0.02, 0.05 and 0.10 m/yr as low, mid and high cases). Therefore, if confirmed by the trial pit tests, this study could justify recalibration of existing closure models to allow for greater erosion rates and would suggest an increased susceptibility of AMD if argillic-dominated pit walls are left exposed to weathering. The trial pit method is thus seen as a key test of the photogrammetric results that may be expected from a large-scale movement of material.

3.2 Manual collection of scree and run-off

The amount of material that was collected at each trial pit significantly varied day to day and across each test location, with quantities varying between a maximum of 1,155 kg and a minimum of 103 kg (Figure 9). It is also noted each trial ran for a different length of time due to access constraints in the working pit. Therefore, averaging over a set amount of time to yield a rate of erosion in kilograms per day was deemed the best way of ensuring that fair comparisons could be made between different waste classes, alteration types and pits (Figure 10).

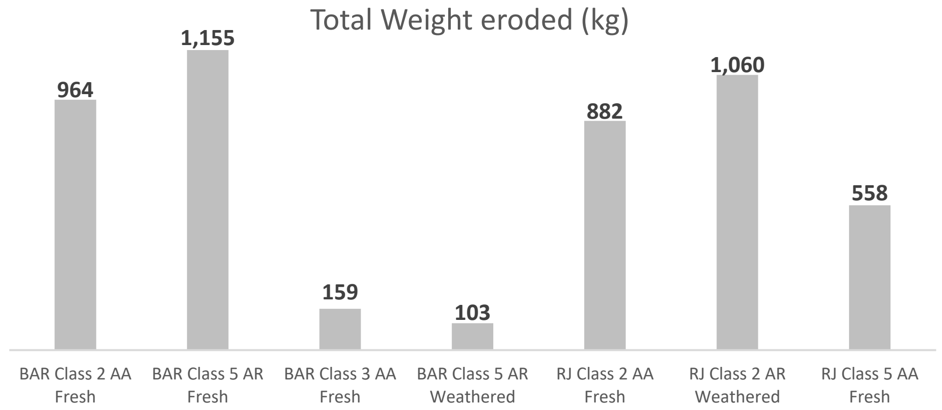


Figure 9 Total solid mass, measured in kilograms, collected for each manual trial location

The conversion to rates in Figure 10 shows that erosion rates in the four trials at the Barani pit show much greater variance than results from Ramba Joring, where three comparable results were obtained. It was noted the observed variance needs to be built into erosion models in the form of ranges to capture high-, low- and mid-case outcomes rather than quoting a single value.

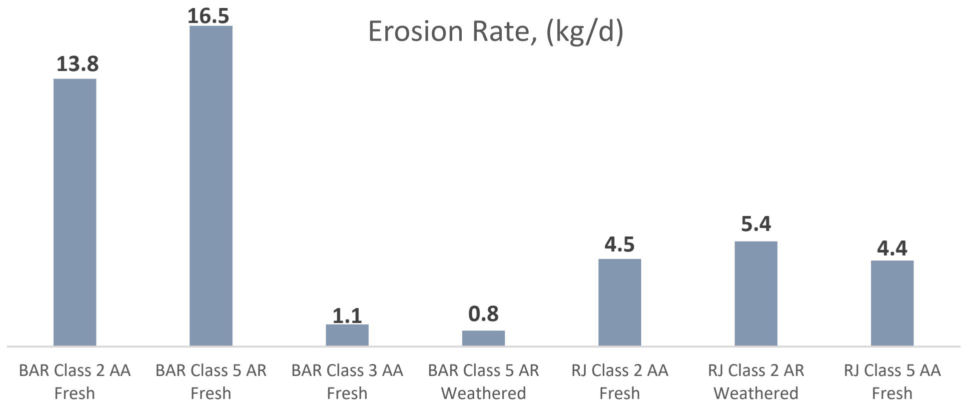


Figure 10 Calculated erosion rate in kilograms per day for each trial location to correct for different trial durations

Furthermore, the overall average rates of material collected were calculated by dividing the total amount of material by the number of trial pits to yield a quantity per trial pit and then dividing by the number of days for which the trial was operating. The total mass collected was 2,318 kg for three combined argillic trial pits and 2,563 kg for four AA trials. The average mass of material collected in each argillic trial was thus 773 kg, which was higher than the 641 kg for each of the AA trials. The total combined amount of time elapsed during the three argillic trials was 392 days, with 532 days of operation for the four AA trials. Dividing the total amount of matter collected by the total amount of time yielded a daily average material accumulation rate of 5.91 kg/d for argillic material and 4.82 kg/d for the AA material for each test location (Figure 11). Argillic material was therefore found to erode approximately 22.5% faster than AA material on a like-for-like basis, based on solid matter collected at a limited number of trial locations (not considering soluble components).

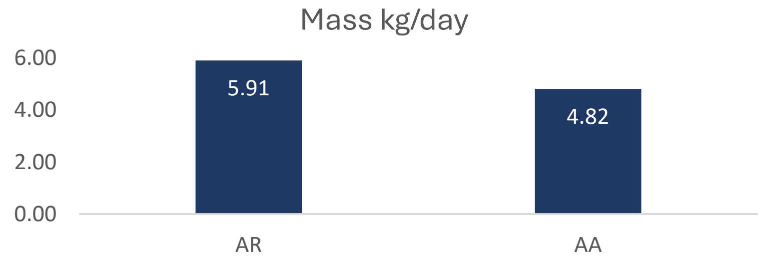


Figure 11 Calculated erosion rate in kilograms per day for each key alteration assemblage, based on field trials covering 30 m²

The area being drained into each trial pit is an important consideration since the amount of material released is expected to be dependent on the catchment area being drained. In practice, two important observations were made:

- Solid material was only captured from the pit wall bench immediately behind the trial pit to a width approximately equal to the width of the trial pit. Thus, taking into account a 10 m bench height and 3 m width of the trial pit, the surface area of pit wall contributing solid material into the trial pit was on average approximately 30 m². Other materials that were eroding either fell to the side of the trial pit or were blocked from rolling down into the pit by higher benches and berms.

- Dissolved material and fine suspended material was likely captured from a similar area as the majority of run-off coming from more elevated benches was directed laterally away from the trial pits, reducing the effective catchment to 30 m² as per the solid material.

The tests were based on a 30 m² catchment which is approximately 0.223% of the area covered by the equivalent 13,454 m² Barani pit photogrammetry study. The rate of material movement was then adjusted to provide a rate of material movement per square metre per day by dividing the mass per trial by the area of each trial (average of 30 m²). The resulting value for argillic material was 0.197 kg/m²/day. The value for AA material was 0.161 kg/m²/day, which retains the proportional relationship of 1:1.225. These rate values are helpful because they allow estimates based on small trial pits to be rapidly scaled up for the areas covered by the photogrammetry study, and to the full extent of the Ramba Joring and Barani pits, for the purposes of source term modelling. Scaling up specifically to the photogrammetry image shown previously in Figure 8, which covered 13,454 m², the amount of material expected to be eroded from argillic areas per day is 2,650 kg/d or 967,409 kg per year (967 t). For the AA material, the estimate is 2,166 kg/d and 790,624 kg per year (791 t). These outputs are judged to be of the same order of magnitude as the independently derived estimate of 1255 t using photogrammetry. Therefore, allowing for the various limitations of the methods used, the outcomes appear to be broadly consistent, providing the acknowledged limitations of the test procedures. The results of the testing can therefore be incorporated into the closure planning process, contributing to water balance modelling and pit fill design.

When manual test results were converted to annual rates and reported as a solid rock thickness equivalent, it was found that argillic material was eroding at 0.03 m/yr and AA material was eroding at 0.024 m/yr in the manual tests under comparable rainfall rates, which is of the same order of magnitude as the results from photogrammetry that indicated erosion in the argillic zone to be 0.10 m/yr equivalent. Further work is required to confirm that the results are mutually supportive over longer periods of time when taking more extreme variances in weather patterns into account. However, these initial results indicate that the original estimates used to populate source term models were broadly representative, and that manual testing has helped to validate the findings from the remote surveying and contributed to validating the erosion modelling approach used by MEM and PTAR at the Martabe site.

In addition to the important role of helping to validate remote photogrammetric measurements, the manual collection of run-off water also enabled detailed analysis of water quality in each trial. Some of the key findings are summarised in Figure 12, which indicates that the highest relative NAG acidity was measured jointly at the Barani Class 5 AR test and RJ Class 2 AR material test, where some Class 3 material was exposed. This result highlights the limitation of relatively low-resolution, resource-type models and the impact of material heterogeneity (e.g. recent research by Wright et al. 2021, 2022), and was based on the Martabe mine, where metre-scale sulphide stringers are not routinely captured in block models but can contribute to the localised detection of AMD during routine monitoring.

The rinse EC result from Barani Class 5 AR material (green bar in Figure 12) is interpreted as evidence of relatively rapid erosion and sulphate release but is also associated with overall circum-neutral rinse pH. This outcome is interpreted by MEM to result from sulphate release due to acid buffering reactions related to naturally occurring carbonate (calcite) which occurs locally in the volcanic andesite (VANH) host lithology.

The term "non-acid forming" (NAF) refers to the overall result of acid and basic reactions and is characterised by circum-neutral NAG pH, and near zero NAG pH 4.5 reading (e.g. "BAR Class 2 AA Fresh") material (darker orange bar in Figure 12). The term potentially acid forming (PAF) refers to an overall net acid result when all sulphide oxidation and acid buffering reactions have been completed. PAF indicators include low Rinse pH, low NAG pH and elevated NAG pH 4.5 exemplified by the "RJ Class 5 AA Fresh" material (red bar in Figure 12).

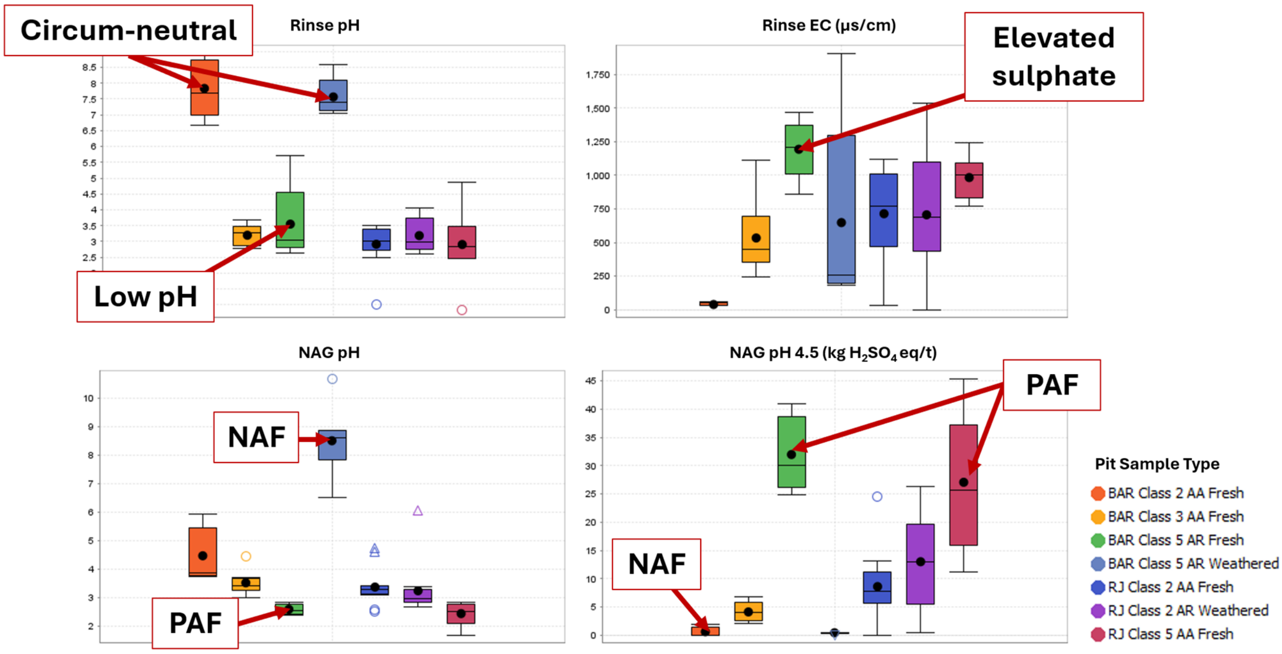


Figure 12 An example of the geochemical analysis for run-off water collected at the seven test locations

Additional long-term monitoring is required to confirm whether the initial results reported in this paper are repeated over a period of years or decades (e.g. closure timescales). A key consideration for the study and for the longer-term closure planning at Martabe is climate change and separating out variations that occur on seasonal, annual and longer climatic timescales, all of which could affect the validity of short-term test results and the longer-term effectiveness of a closure plan.

The seven main trial pit studies were conducted in parallel with the pit wall photogrammetric scanning over a period of 20 weeks, which saw variable but often heavy rainfall consistent with the tropical setting. The plot in Figure 13 shows rainfall versus time versus amount of material collected, and records two main periods of wetter conditions and two main low rainfall periods, shown by the 14-day moving average. The coloured lines on each plot refer to the amount of each waste class material collected and show a consistent pattern at each trial pit, and across the two main pits at Ramba Joring and Barani. The lowest rates of material collection occur during the low rainfall events and the highest collections occur during the higher rainfall periods, suggesting that an overall relationship between rainfall and erosion can be approximated.

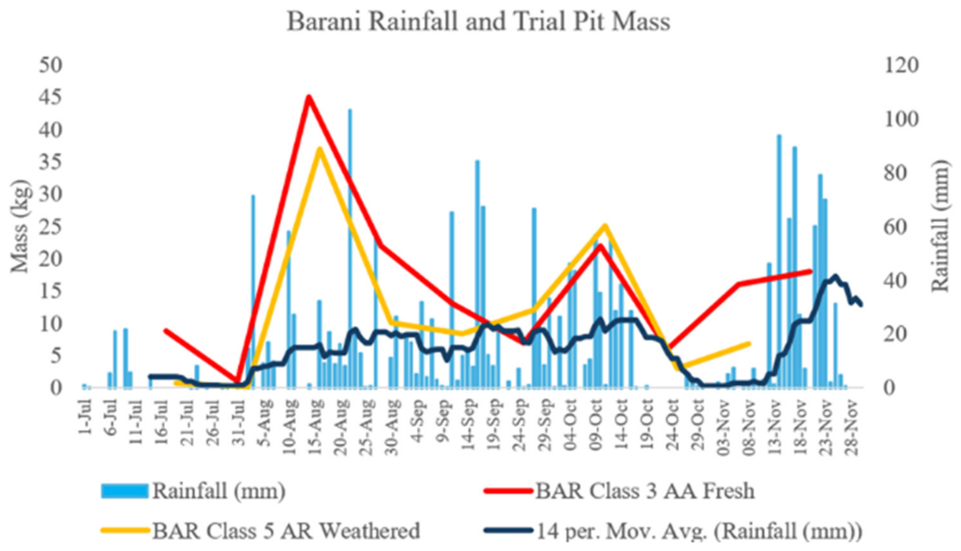


Figure 13 An example of sample mass collected versus rainfall at the Barani trial pits

The second key consideration for the closure design is the characterisation of run-off generated from the pit walls. Assessments of contact water and solid materials collected during the trial pit study reveal that in general, argillic materials generated lower pH, released more sulphate as a proxy for sulphide oxidation and had higher concentrations of indicator metals, e.g. Cu. Exceptions were noted, particularly where Class 3 material tended to generate low pH and high metal release, irrespective of the alteration type. Those areas which captured run-off from rainwater that had been in contact with Class 5 material tended to show elevated manganese, which is thought to be sourced from acid neutralising reactions with manganese-bearing carbonates. There were more than 500 individual measurements and tests conducted across the seven trial pits. However, the key trial pit outcomes were a general decrease in water quality with increasing sulphide content, and a general increase in erosion with increasing clay content and increased rainfall intensity.

4 Discussion

In general, the rate of mass mobilisation estimated from photogrammetry over the short-term period the trial was run is comparable to that calculated from the amount of material collected in the trial pits, indicating overall the outcomes are fair and a reasonable representation of reality in the pits. Results of the direct monitoring using photogrammetry support visual observations that rates of pit wall erosion are generally at the higher end of the range of previously estimated values prior to the study, with the highest rates of erosion seen in AR zones, irrespective of their sulphide content, based on comparable rainfall rates. Argillic material eroded 23% faster than AA material on a calibrated basis, which is less of a difference than expected, based on initial uncalibrated estimations which anticipated a five- or 10-fold greater erosion rate for argillic material compared to AA material. The rates of erosion for AA material were much closer to those rates of the argillic material and at or above the mid- and high-case estimates put forward prior to the trials being undertaken.

Low pH and elevated metal concentrations including manganese were noted in run-off water collected at the base of a zone dominated by Class 5 AA material, which was expected to yield overall net neutral run-off. The trial suggests acid production rates are, at present, greater than the rates at which acidity can be offset by neutralising reactions, which is interpreted to be a function of high erosion rates in the argillic material. Therefore, exposed pit walls displaying Classes 3, 4 and 5 materials can generate AMD under the rates of erosion observed in the trial.

Erosion rate assessments based on solid scree, run-off-entrained particulate material and material in solution indicate that the basal pit void area expected to form a pit lake (such as the base of the Barani pit) can be expected to fill up with erosion-related debris and scree over an approximate 50-year time span. This finding suggests that long-term pit wall stability is an important consideration for closure planning at Martabe. This study helped to show that using partial in pit filling could provide a practical engineering solution to prevent the development of overly steep pit walls which, based on this study and others like it, are more prone to release material than lower gradients. Stabilising vegetation and using cover systems that restrict oxygen ingress to reactive sulphide-bearing materials, which reduces oxidation and reaction rates, would further restrict the potential for metal and acidity release over the long term. Ongoing work seeks to monitor erosion patterns over longer periods to help improve current structural and water quality models.

5 Conclusion

Overall, the study has shown the benefits of collecting empirical data with which to build improved erosion and source term models. Erosion rates were generally found to be at the upper end of the range of pre-trial estimations for argillic material and exceed estimates for advanced argillic materials, supporting the value of empirical data to validate/test assumptions based on modelling/desk/academic-based assessments. The measurable separation in erosion rates and the geochemical characteristics of different types of waste material at the Martabe site demonstrate the need for site- and pit-specific studies. These studies provide valuable information to guide mining and environmental closure practices that can yield more targeted and efficient long-term management of exposed pit walls and run-off. Better management of long-term erosion can result in tangible “win-win” benefits for water quality in terms of mitigating potential acid and metalliferous drainage, and with respect to reducing environmental costs for the mine operator. A key outcome of this study for long-term closure planning has been the recognition that partial in-pit filling has the potential to offer lower closure risks relating to AMD and more flexible long-term rehabilitation options than opting for pit lakes. This is because in-pit filling provides an engineering solution to reduce pit wall erosion as it includes regrading and rehabilitation of slopes at lower gradients. This will reduce AMD risk due to larger areas of clean run-off being generated from rehabilitated slopes, lower potential groundwater discharge due to high run-off from rehabilitated areas and greater mine flexibility because of the potential to use void space for waste disposal. The findings of this study therefore contribute to achieving the guideline principles of compliance with applicable environmental laws, regulations and operating permits, the prevention of pollution, the safe disposal of tailings and waste rock, successful implementation of mine closure, protection of biodiversity and continual improvement in environmental performance.

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